Available online at www.sciencedirect.com

Agriculture, Ecosystems and Environment 97 (2003) 295–308

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

Soil erosion prediction using RUSLE for central Kenyan highland conditions

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Received 15 April 2002; received in revised form 5 November 2002; accepted 9 December 2002

Abstract

Soil erosion by water is serious global problem. In Africa, about 5 Mg ha^{-1} of productive topsoil is lost to lakes and oceans each year. This study was conducted at the Kianjuki catchment in central Kenya to predict annual soil loss using the Revised Universal Soil Loss Equation (RUSLE Version 1.06) to determine the erosion hazard in the area and target locations for appropriate initiation of conservation measures. All factors used in RUSLE were calculated for the catchment using local data. The rainfall erosivity *R*-factor was 8527 MJ mm ha^{-1} h^{-1}per year and the annual average soil erodibility *K*-factor was 0.016 Mg h MJ^{-1} mm^{-1}. Slopes in the catchment varied between 0 and 53% with steeper slopes having overall *LS*-values of over 17. The *C*-factor values were computed from existing cropping patterns in the catchment, including corn–bean (*Zea mays*–*Phaseolus vulgaris*) 1-year rotation, coffee (*Coffea arabica*), and banana (*Musa sapientum*). Support practice *P*-factors were from terraces that exist on slopes where coffee is grown. Total annual soil loss predictions varied from one overland flow segment to the next and ranged from 134 Mg ha^{-1} per year for slopes with average *LS*-factors of 0–10 to 549 Mg ha^{-1} per year for slopes with average *LS*-factors of 20–30, which is more than the estimated soil loss tolerance (*T*) for the area of 2.2–10 Mg ha^{-1} per year. Using 3 years of field data, the RUSLE model was able to pinpoint site-specific erosion hazards associated with each overland flow segment in the catchment for different cropping patterns and management practices. This work highlights the severity of erosion in tropical highlands of east Africa and gives suggestions on possible intervention strategies; however, there is still a need for developing more long-term data to validate the model to suit local agro-ecological conditions.
Published by Elsevier Science B.V.

Keywords: Erosion modeling; Erosion prediction; RUSLE; Soil conservation; Soil loss; Kenya

1. Introduction

Soil erosion increased throughout the 20th century. About 85% of land degradation in the world is associated with soil erosion, most of which occurred since the end of World War II, causing a 17% reduction in crop productivity (Oldeman et al., 1990). In assessing

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0167-8809/03/$ – see front matter. Published by Elsevier Science B.V.
doi:10.1016/S0167-8809(03)00011-2

the economics of soil conservation in Kenya, erosion control under natural and agricultural conditions will be important for maintaining current agricultural production levels (Pagiola, 1990). There is also a stated need to identify critical areas for targeting limited erosion control funding. Erosion prediction models can help address long-range land management planning under natural and agricultural conditions. Even though it is hard to find a model that considers all forms of erosion, some models were developed specifically to aid conservation planners in identifying areas where introducing soil conservation measures will have the most impact on reducing soil loss.

The Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997) model, although developed to predict water erosion in temperate climates, is easier to adapt to tropical climates than other existing models. RUSLE is an empirically based model, founded on the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978), but is more diverse and includes databases unavailable when the USLE was developed (Renard et al., 1997). RUSLE is designed for use at the runoff plot or single hillslope scales. The RUSLE model enables prediction of an average annual rate of soil erosion for a site of interest for any number of scenarios involving cropping systems, management techniques, and erosion control practices. Erosion rates of ungauged catchments can also be predicted using RUSLE by using knowledge of the catchment characteristics and local hydro-climatic conditions (Garde and Kathyari, 1990). The results from erosion prediction are compared to estimated soil-loss tolerance (T) values for the area in question, which denotes the maximum rate of soil erosion that can occur and still permit crop productivity to be sustained economically. An infinite number of slope lengths exist in a field. In RUSLE, erosion can be calculated for several slope lengths and the results averaged according to the area represented by each slope length to obtain an erosion rate for a field. Results from representative fields can be combined to estimate erosion rates for an entire watershed.

RUSLE computes the average annual erosion expected on hillslopes by multiplying several factors together: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and support practice (P). The values of these factors are determined from field and laboratory experiments (Renard et al., 1997). The R-factor is measured as the product (EI) of total storm energy (E) and the maximum 30-min intensity (I_{30}) for all storms over a long time (Brown and Foster, 1987). The EI parameter quantifies the effects of raindrop impact and reflects the amount and rate of runoff likely to be associated with the rain (Wischmeier and Smith, 1978). The K-factor reflects the ease with which the soil is detached by splash during rainfall and/or by surface flow, and therefore shows the change in the soil per unit of applied external force of energy. This factor is related to the integrated effect of rainfall, runoff, and infiltration and accounts for the influence of soil properties on soil loss during storm events on sloping areas. For tropical soils, unstable soil aggregates, modified silt, sand, and the corresponding base saturation are used to determine K (El-Swaify and Dangler, 1976). The K-factor derived from the USLE nomograph (Wischmeier and Smith, 1978) is applicable to tropical soils that have kaolinite as the dominant clay mineral, but less applicable where Vertisols dominate (Roose, 1977). The LS-factor accounts for the effect of slope length and slope gradient on erosion. RUSLE provides conversion tables for determining LS on uniform slopes (Renard et al., 1997). Soil loss increases more rapidly with slope steepness than it does with slope length (McCool et al., 1987). The C-factor measures the effects of all interrelated cover and management variables (Renard et al., 1991). Values of C can vary from near zero for well-protected soils to 1.5 for finely tilled, ridged surfaces that are highly susceptible to rill erosion. RUSLE software provides extensive crop database values, including some tropical crops, which are used to evaluate the C-factor, especially when plant growth characteristics are known, or the user may develop a more appropriate database from experimental data (Renard et al., 1997). The P-factor is the ratio of soil loss with specific support practice to the corresponding loss with up and downslope tillage. These practices proportionally affect erosion by modifying the flow pattern, gradient, or direction of surface runoff and by reducing the amount and rate of runoff (Renard and Foster, 1983). Values for P-factor range from about 0.2 for reverse-slope bench terraces, to 1.0 where there are no erosion control practices (Wischmeier and Smith, 1978). On croplands, support practices include contouring (tillage and planting on or near the contour), strip cropping, terracing, and subsurface drainage and their values can be calculated in conjunction with the R, K, and LS-factors to reflect their effect on reducing runoff (Renard et al., 1997).

The International Center for Research in Agroforestry (ICRAF) in collaboration with national agricultural research institutions in east Africa has set up the African Highland Initiative program (AHI). The AHI program focuses on conserving soil and increasing plant productivity of watershed areas using agroforestry intervention approaches with the participation of the local community. In central Kenya, AHI chose four catchments (Ndunduri, Ivondo, Kambita and Kianjuki) to be pilot projects for the sub-humid and humid highlands of central Kenya. However, before any meaningful soil conservation intervention methods could be implemented, there was a need to determine the erosion hazard associated with these catchments. For this study, the erosion hazard was evaluated for the Kianjuki catchment.

The objectives of this study were to predict long term soil loss in the Kianjuki catchment using RUSLE by determining: (1) rainfall and runoff erosivity R-factor; (2) soil erodibility K-factor; (3) slope length and steepness LS-factor; (4) cover and management C-factor; and (5) support practice P-factor. The working hypothesis for this study was that soil loss from the catchment would be higher than the soil loss tolerance T that has been estimated for the area, which is 2.2–10 Mg ha^{-1} per year depending on the depth of the A-horizon, thus will warrant implementing soil conservation intervention measures.

2. Methods

This study was conducted at the Kianjuki catchment area in the Embu District of central Kenya. Located about 45 km south–southeast of Mt. Kenya and 125 km northeast of Nairobi, this site is representative of most of the east African highlands for climate, soils, slopes, and vegetation. It is located at 00°30′S latitude, 37°27′E longitude, and 1480 m above sea level (O'Neill et al., 1993). Average annual rainfall is 1500 mm, which comes during two rainfall (growing) seasons called the long rains (March–September) and the short rains (October–February). Soils are classified as Humic Nitosols (FAO-UNESCO, 1988) or Typic Palehumults (USDA, 1975).

The average soil loss (A) due to water erosion per unit area per year (Mg ha^{-1} per year) was quantified, using RUSLE 1.06b (USDA-ARS, 2001; Renard et al., 1997) by the following equation:

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

where A is the average soil loss due to water erosion (Mg ha^{-1} per year), R the rainfall and runoff erosivity factor (MJ mm ha^{-1} h^{-1} per year), K the soil erodibility factor (Mg h MJ^{-1} mm^{-1}), L the slope length (m), S the slope steepness (%), C the cover and management practice factor, and P the support practice. RUSLE, which was developed for field use in the USA, uses inputs and produces output in US customary units, thus factor values were converted to SI units (Système International d'Unités) for presentation here.

2.1. Rainfall and runoff erosivity R-factor

The R-factor is usually calculated as an average of EI values measured over 20 years to accommodate apparent cyclical rainfall patterns. Since this catchment region did not have long-term rainfall records, the R-factor was computed using the procedure described by Renard and Freidmund (1994). For this, storm events and monthly rainfall totals are used to calculate an R-factor based on short term minute by minute rainfall data. Using an automatic tipping rain gauge that tipped each minute it rained, rainfall was measured throughout 1 year in the catchment. The data were used to calculate the individual total storm kinetic energy (E) in MJ ha^{-1} and the maximum 30-min intensity (I_{30}) in mm h^{-1}. Using this data, the rainfall erosivity factor (R) in MJ mm ha^{-1} h^{-1} per year was calculated as:

$$R = \frac{\sum_{i=1}^{j} (EI_{30})_i}{N} \quad (2)$$

where $(EI_{30})_i$ is the EI_{30} for storm i, j the number of storms in an N year period. The total storm kinetic energy E, in MJ ha^{-1} mm^{-1} was calculated by:

$$E = \sum_{i=1} e_r \,\Delta V_r \quad (3)$$

$$e_r = 0.29[1 - 0.72 \exp(-0.05 i_r)] \quad (4)$$

where e_r is the rainfall energy per unit depth of rainfall (MJ ha^{-1} mm^{-1} h^{-1}) (Brown and Foster, 1987), I_r the rainfall intensity for a particular increment in a rainfall event (mm h^{-1}), and ΔV_r the duration of the increment over which I_r is constant in hours (h).

At the study site, daily rainfall totals were available for 12 years (1987–1991, 1993–1999) collected by the Embu meteorological station, under the Ministry of Agriculture, Kenya. A relationship was developed from the minute-by-minute data by using Eq. (2) and utilizing the daily rainfall totals available for 12 years to develop the long-term *R*-factor for the study site. This value was then used in RUSLE to predict annual soil loss for the catchment.

2.2. Soil erodibility K-factor

Soil erodibility *K*-factor was determined using inherent soil properties, following the El-Swaify and Dangler (1976) procedure for tropical soils, which uses the percent-modified silt (0.002–0.1 mm), percent modified sand (0.1–2 mm), base saturation, percent unstable aggregates, and percent very fine sand. The values for the measured soil properties were used to calculate *K* using the following equation:

$$K = -0.03970 + 0.00311X_1 + 0.00043X_2 + 0.00185X_3 + 0.00258X_4 - 0.00823X_5 \quad (5)$$

where X_1 is the percent unstable aggregates <0.250 mm, X_2 is the product of the percent of silt (0.002–0.01 mm) and sand (0.1–2 mm) present in the sample, X_3 is the percent base saturation of the soil, X_4 is the percent silt present (0.002–0.050 mm), and X_5 is the percent sand in the soil (0.1–2 mm). This equation results in a *K*-factor with units of ton acre h [hundreds of acre ft tonf in.]$^{-1}$, thus the result was divided by 7.59 to obtain the equivalent value in SI units of Mg h MJ^{-1} mm^{-1} (Renard et al., 1997).

The percent of unstable aggregates less than 0.250 mm and sand between 0.1 and 2.0 mm was determined by wet sieving following procedures described by Franzmeier et al. (1977). A 10 g soil sample was pre-wetted overnight to reduce the effect of slaking. The soil was then introduced into a nest of oscillating sieves of 4.76, 2.0, 1.0, 0.5, and 0.21 mm immersed in deionized water. Any soil that passed through the 0.21 mm sieve constituted the unstable aggregate fraction for this procedure. The material in each sieve was gently crushed under running water, allowing the smaller particles to be washed through the sieve, while the sand was retained on the sieve. The sand was then oven-dried in the sieves at 105 °C for 24 h. The sand was then passed though a vibrating nest of sieves that separated it into very coarse sand (1–2 mm), coarse sand (0.5–1 mm), medium sand (0.25–0.5 mm), fine sand (0.10–0.5 mm), and very fine sand (0.05–0.1 mm).

Percentage clay and silt present in the soil and particle size distribution was determined by the pipette method (Gee and Bauder, 1986). Briefly, 10 g of soil were dispersed using sodium hexametaphosphate, shaken overnight, and then followed by a period of sedimentation. Aliquots for particle size distribution were drawn from the samples, using a pipette at different times, depending on the size fraction in question.

Cation exchange capacity (CEC) and exchangeable acidity (EA) were measured (Summer and Miller, 1996) and used to calculate the percent base saturation (BS).

Additionally, total carbon was determined as by dry combustion (CHN-600, Leco Corp., St. Joseph, MI), and since there were no carbonates present in the soil samples, total carbon was equivalent to total organic carbon.

2.3. Slope length and steepness LS-factor

The catchment, which occupies approximately 120 ha (297 acres), was divided into 35 sub-units or segments that were considered to have uniform slopes (Fig. 1). These segments were then grouped into drainage profiles that had independent runoff flow patterns during rainfall storms. The slope lengths for each segment, as well as the percent slope, were measured using a global positioning unit (Magellan GPS 75, Magellan Consumer GPS Products, San Dimas, CA) and an inclinometer (T2-inclinometer, US Digital Corporation, Vancouver, WA), respectively. These data were used as input for RUSLE to generate overall *LS*-factors and equivalent slopes for each segment in the profile. Most slopes in each profile exceeded the maximum 304 m (1000 feet) allowed in RUSLE calculation. Measurements for an overall *LS* were therefore taken from the top of each profile to a position downslope where deposition was more

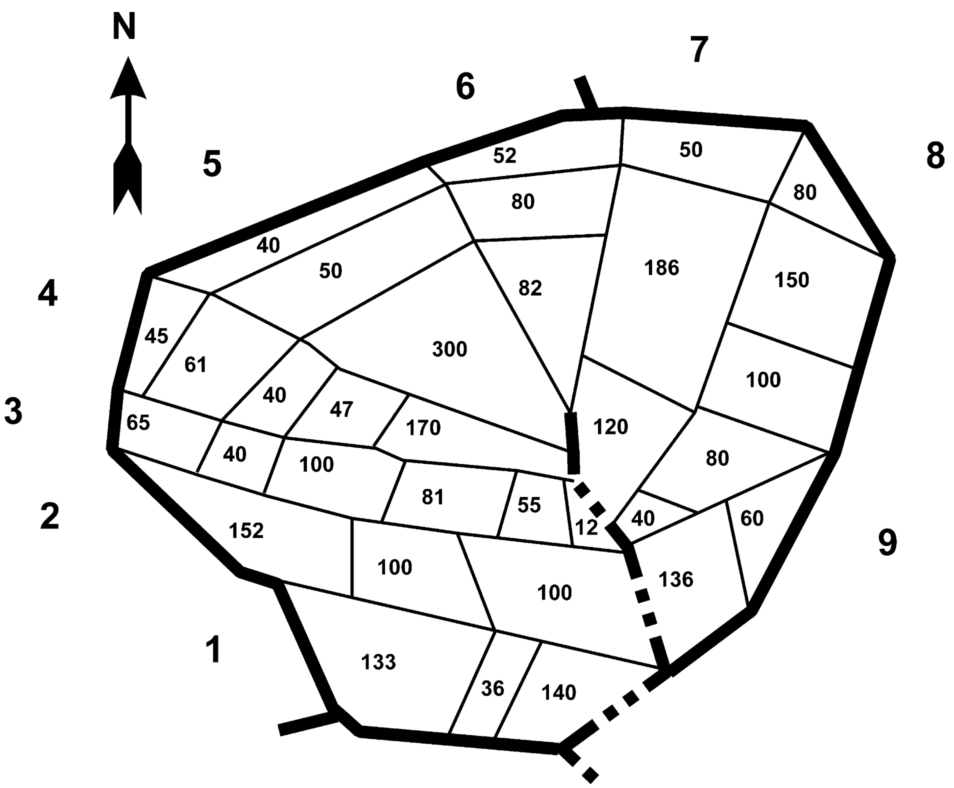

Fig. 1. Diagram of the Kianjuki catchment in central Kenya showing the nine profiles with slope lengths (m) for each segment. Segments are numbered from the top of each profile.

than detachment and the length was less than 304 m. The top of the profile was chosen at a point of origin for overland flow. Methods for selecting slopes are detailed in the RUSLE documentation (McCool et al., 1997).

2.4. Cover management C-factor

Crop growth data as well as cropping patterns and land use systems from Kianjuki catchment were used to create a crop database for RUSLE. The predominant cropping systems included corn–bean (*Zea mays–Phaseolus vulgaris*) 1-year rotation, coffee (*Coffea arabica*), and banana (*Musa sapientum*). Using the database, RUSLE produced the corresponding *C*-factor values for the catchment. The crop database required parameters such as residue mass at harvest, row spacing, surface and subsurface residue decomposition rates, residue mass at 30, 60, and 90% cover, and root mass density in the top 10 cm soil at different stages of growth. Since the catchment has about 100 farms that have an average size of 1.2 ha with different cropping patterns and management, the *C*-factor for each uniform slope was weighted by the percent of the crop present in each segment and then averaged over the profile.

The *C*-factor evaluation incorporates cropping and management factors that include interrelated effects of cover, crop sequence, cultural practices, and length of growing season (Wischmeier and Smith, 1978). Within the study catchment, multiple families own land within a single profile and use different cropping and cultural practices. The problems arising from this complexity were overcome by dividing the slope profile into segments with uniform slopes, making the evaluation of cropping pattern easier.

2.5. Support practice P-factor

An overall P-factor was computed as a product of P-factors for individual support practices that are used in combination to reduce erosion. Such practices include terracing, contour tillage, and permanent barriers or strips. For this catchment, the P-factor for terracing was the only one used since the other practices were absent or not consistent throughout the slopes. Values for the terracing factor were available from the RUSLE database software. Its value varied depending on the slope length and steepness.

3. Results and discussion

3.1. Rainfall and runoff erosivity R-factor

The rainfall events and the erosion indices (EI), for the 1-year minute-by-minute rainfall measured form September 1998 through August 1999 were well correlated ($r^2 = 0.86$ for $P = 0.05$ Fig. 2) and gave this relationship:

$$EI = 9.533d \tag{6}$$

where EI is the erosion index, and d the total amount of rainfall (mm) in a continuous daily rainfall event that exceeds 13 mm. There were eleven storms that exceeded 13 mm during this drought year.

Using Eq. (6) with the 12 years of rainfall data, the average annual rainfall erosivity factor R (average annual EI) was calculated, using Eq. (2) and found to be 8527 MJ mm ha^{-1} h^{-1} per year [501 hundreds of foot tonf inch acre^{-1} h^{-1} per year] (Table 1), for a mean annual rainfall of 1500 mm. The 12 years included not only data from the drought years when the field data was accumulated, but also data from the wet years including the rains that were influenced by the El Niño effect and were up to four times higher than other years.

This R-factor was greater than the 2800 MJ mm ha^{-1} h^{-1} per year observed in neighboring Zimbabwe where the mean annual rainfall is 700–800 mm (Stocking and Elwell, 1976), and where for every

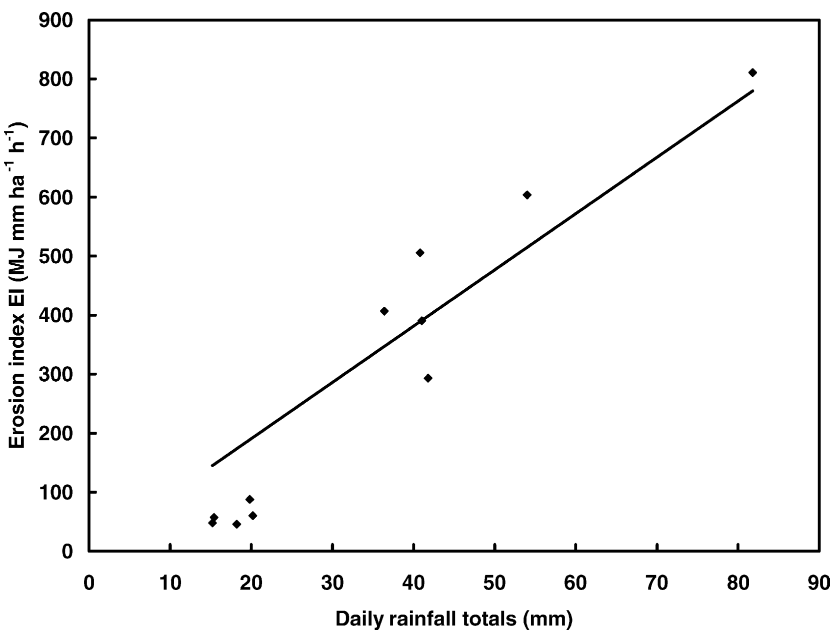

Fig. 2. Daily rainfall totals and erosion indices EI ($r^2 = 0.86$, $P = 0.05$) for the Kianjuki catchment in central Kenya (September 1998–August 1999). Each point represents the erosion index associated with each recorded storm. Rainfall intensity was recorded once a minute.

Table 1
EI index and the average annual rainfall and runoff erosivity *R*-factor for Kianjuki catchment in central Kenya

Year	*EI* index[a] (MJ mm ha^{-1} h^{-1})
1987	7091
1988	13566
1989	7799
1990	10940
1991	3308
1993	8492
1994	11552
1995	8314
1996	5662
1997	12521
1998	9427
1999	3649
Average annual *R*-factor[b]	8527[c]

[a] *EI* is the product of total storm energy (*E*) and the maximum 30-min intensity (I_{30}).
[b] *R*-factor in MJ mm ha^{-1} h^{-1} per year.
[c] To convert to US customary units divide by 17.02 (501 foot tonf inch $acre^{-1}$ h^{-1} per year).

Table 2
Soil properties for use in calculating the RUSLE *K*-factor for the Kianjuki Catchment in central Kenya

Fraction	Percentage
Clay (<0.002 mm)	65
Very fine sand (0.05–0.10 mm)	2
Silt (0.002–0.05 mm)	27
Sand (0.05–2 mm)	8
Sand (0.1–2 mm)	6
Total Organic matter	2.8
Base saturation	58
Unstable aggregates[a]	10
Permeability class	3 (moderate)
Soil structure code	2 (fine granular)

[a] Aggregates that pass through the 0.21 mm sieve (unstable aggregates).

100 mm increment over the 300 mm mean annual rainfall, *R* increased by 400 MJ mm ha^{-1} h^{-1} per year. The Fournier's index has been used to calculate annual *R*-factor values for West Africa that ranged between 8500 and 12,765 MJ mm ha^{-1} h^{-1} per year for average annual rainfall between 1000 and 1500 mm (Arnoldus, 1980). Effective rainfall data in South Africa, which includes individual storm events of sufficient duration to be used in calculating *EI*, were used to calculate an *R*-factor of 9520 MJ mm ha^{-1} h^{-1} per year for an average annual rainfall of 1200 mm (Smithen and Schulze, 1982). The *R*-factor determined for the Kenyan catchment is within the acceptable range for use in RUSLE, despite having only a few years of data.

3.2. Soil erodibility K-factor

The soils were uniform and similar for the whole catchment. The soils were over 2-m deep, with a clay texture, having over 65% clay and very little sand, and a high base saturation (Table 2). Using Eq. (5) and the soil properties data, the *K*-factor for the Kianjuki soils was calculated as 0.016 Mg h MJ^{-1} mm^{-1} (0.12 t acre h [hundreds of acre ft-tonf in.]$^{-1}$). These results were similar to the comparable value in the *K*-nomograph (Wischmeier and Smith, 1978), which was 0.018 Mg ha h ha^{-1} MJ^{-1} mm^{-1} (0.14 t acre h [hundreds of acre ft-tonf in.]$^{-1}$).

K-factors for some African tropical soils have been estimated using the USLE with US customary units of ton acre h[hundreds of acre ft tonf in.]$^{-1}$. Barber et al. (1979) estimated a *K*-factor for the Nitosols in central Kenya as 0.05, while Mati (2000) estimated it as 0.23. Although there is no information on the variation of *K* with time and season, the difference in time and location, as well as in management practices would contribute to observed differences in *K*. The *K*-factors for tropical soils usually increase when soils are cultivated and vary with soil type, season of the year, and cultural practices (Roose and Sarrailh, 1989).

3.3. Slope length and steepness LS-factor

The catchment was divided into 35 segments of approximately uniform slope that fitted into the 9 drainage profiles (Fig. 1). The length and slope of each segment were measured and the *LS*-factor for each segment was computed using RUSLE 1.06 (Table 3). The *LS*-factors varied throughout the catchment depending on the existing *C*- and *P*-factors, but generally, the steeper the slopes the higher the *LS*-factors. The *C*- and *P*-factors affect the way runoff flows on slopes and the RUSLE software allows their incorporation to determine final *LS* of each segment.

The slopes in this catchment exhibited a complex hillslope profile that was convex along the upper portion and concave along the lower portion. Complex catchments exhibit the lowest level of soil loss

Table 3
Hillslope profiles and segments with the associated *LS*-factors and weighted *C*-factors, for the Kianjuki Catchment in central Kenya

Profile	Segment	Slope (%)	*LS*-factor	Dominant Crops	Crop *C*-factor	Land occupied by crop	*C*-factor (%)	Weighted *C*-factor
1	1	20	5.1	Coffee	0.394	70	0.0758	0.379
				Corn/bean	0.343	30	0.1029	
	2	15	23	Corn/bean	0.343	50	0.1715	0.247
				Coffee	0.394	10	0.0394	
				Banana	0.089	40	0.0356	
	3	5	0.8	Corn/bean	0.343	40	0.1372	0.343
				Banana	0.089	10	0.0089	
				Coffee	0.394	50	0.197	
2	1	20	5.3	Corn/bean	0.343	20	0.0686	0.353
				Banana	0.089	10	0.0089	
				Coffee	0.394	70	0.2758	
	2	24	7.57	Corn/bean	0.343	20	0.0686	0.353
				Banana	0.089	10	0.0089	
				Coffee	0.394	70	0.2758	
3	1	12	2.0	Corn/bean	0.343	80	0.2744	0.292
				Banana	0.089	20	0.0178	
	2	20	3.4	Banana	0.089	80	0.0712	0.140
				Corn/bean	0.343	20	0.0686	
	3	30	7.6	Coffee	0.394	90	0.3546	0.364
				Banana	0.089	10	0.0089	
	4	38	9.0	Coffee	0.394	90	0.3546	0.364
				Banana	0.089	10	0.0089	
	5	40	8.1	Banana	0.089	100	0.089	0.139
4	1	16	2.7	Corn/bean	0.343	100	0.343	0.343
	2	24	4.9	Coffee	0.394	100	0.394	0.394
	3	35	6.2	Coffee	0.394	80	0.3152	0.384
				Corn/bean	0.343	20	0.0686	
	4	40	7.6	Coffee	0.394	60	0.2364	0.374
				Corn/bean	0.343	40	0.1372	
	5	53	17	Banana	0.089	30	0.0267	0.287
				Coffee	0.394	40	0.1576	
				Corn/bean	0.343	30	0.1029	
5	1	14	2.2	Coffee	0.394	60	0.2364	0.374
				Corn/bean	0.343	40	0.1372	
	2	26	5.0	Coffee	0.394	100	0.394	0.394
	3	40	16.2	Coffee	0.394	80	0.3152	0.358
				Corn/bean	0.343	10	0.0343	
				Banana	0.089	10	0.0089	
6	4	10	2.1	Coffee	0.394	50	0.197	0.343
				Corn/bean	0.343	40	0.1372	
				Banana	0.089	10	0.0089	
	5	20	4.3	Corn/bean	0.343	30	0.1029	0.318
				Banana	0.089	20	0.0178	
				Coffee	0.394	50	0.197	
	6	55	12.7	Coffee	0.394	70	0.2758	0.353
				Corn/bean	0.343	20	0.0686	
				Banana	0.089	10	0.0089	
7	1	35	6.8	Coffee	0.394	70	0.2758	0.303
				Banana	0.089	30	0.0267	

Table 3 (*Continued*).

Profile	Segment	Slope (%)	*LS*-factor	Dominant Crops	Crop *C*-factor	Land occupied by crop	*C*-factor (%)	Weighted *C*-factor
	2	45	15.1	Coffee	0.394	90	0.3546	0.364
				Banana	0.089	10	0.0089	
	3	19	4.6	Banana	0.089	50	0.0445	0.216
				Corn/bean	0.343	50	0.1715	
8	1	40	9.4	Coffee	0.394	70	0.2758	0.303
				Banana	0.089	30	0.0267	
	2	45	13.8	Coffee	0.394	90	0.3546	0.364
				Banana	0.089	10	0.0089	
	3	25	6.1	Corn/bean	0.343	70	0.2401	0.358
				Coffee	0.394	30	0.1182	
9	1	29	6.0	Coffee	0.394	80	0.3152	0.358
				Corn/bean	0.343	10	0.0343	
				Banana	0.089	10	0.0089	
	2	10	1.3	Coffee	0.394	70	0.2758	0.328
				Banana	0.089	20	0.0178	
				Corn/bean	0.343	10	0.0343	

compared to concave, uniform, and convex slopes (Renard et al., 1997). This is because the shape of the hill slope profile affects soil loss rates due to the changes in the length and gradient characteristics along the hillslope. In this study rill formation, especially on tilled ground was noticeable at the start of the rainy season as erosion continually increased on the steep slopes during each season.

Soils of the Kianjuki catchment are classified as not prone to rill or interrill erosion because they have a high percentage of clay (>65%) (Renard et al., 1997). However, there is generally a threshold length at which rilling will start to occur especially since runoff usually varies with steepness more on low slopes but not on steep slopes greater than 8% (McCool et al., 1987). The Kianjuki catchment exhibited slopes greater than 8%, many exceeded 50%, and some approached 100%. This resulted in a higher *LS*-factor, and thus, despite the soil type factor in rill formation, the slopes were classified as being prone to rill and interrill erosion. The greater slopes resulted in increased overland flow and rilling and concentrated flow depth and velocity in developing gullies.

3.4. Cover management C-factor

The cover management factor was calculated from four predominant crops (coffee, banana, and corn–bean in rotation). For each of these crops, values for residue remaining after harvest (kg ha^{-1}), row spacing (m), and plant population (number of plants ha^{-1}) were estimated. The RUSLE database then assigned values for surface and subsurface residue decomposition constants and residue at 30, 60, and 90% cover by performing cyclic iterations on 15-day growth intervals (Table 4). These iterations included model database estimates for plant root mass in the top 10 cm of soil, percent canopy cover, and crop canopy fall height at each of the 15 days. Values for these estimates were calculated by the RUSLE routine and were in line with the *EI* values entered for the *R*-factor calculation. For coffee and banana, the data were entered for 3 years since these were perennial crops. The resultant RUSLE output was the *C*-factor for each cropping pattern used in the catchment. The overall *C*-factors for crops were 0.314 for the corn–bean 1-year rotation, 0.415 for the perennial coffee, and 0.122 for the perennial banana. For each segment in each profile, these factors were weighted by the percentage they occupied on the land and an average final *C*-factor was defined for each segment. The weighted average for all the crops resulted in a lower *C*-factor than when only one crop was considered.

Soil loss in the catchment was accelerated because there was less than 10% surface cover during most of the year, and the only significant canopy cover

Table 4
C-factor input data for Coffee, Banana, Corn, and bean cropping patterns for the RUSLE database at Kianjuki catchment, central Kenya

Crop	Residue at harvest (Mg ha^{-1})	Row spacing (m)	Plant population (plants ha^{-1})	Surface residue decomposition constant	Sub-surface residue decomposition constant	Residue at 30% cover (Mg ha^{-1})	Residue at 60% cover (Mg ha^{-1})	Residue at 90% cover (Mg ha^{-1})
Corn	400	0.76	51900	0.016	0.016	1000	2700	6700
Bean	1500	0.3	27000	0.025	0.025	670	1800	2200
Coffee, 1st year	2200	1.5	3600	0.015	0.015	670	1700	4300
Coffee, 2nd year	2200	1.5	3600	0.015	0.015	670	1700	4300
Coffee, 3rd year	2800	1.5	3600	0.015	0.015	670	1700	4300
Banana, 1st year	20000	2.4	2700	0.015	0.015	1300	3400	6700
Banana, 2nd year	22000	2.4	3000	0.018	0.018	1300	3400	6700
Banana, 3rd year	22000	2.4	3000	0.018	0.018	1300	3400	20000

throughout the year was the 25% canopy associated with the coffee bushes. Woodlots in the Kianjuki catchment occupied less that 1% of the land. This is attributable to the pressure on land for arable farming (Kohler, 1987; Huber and Opondo, 1995) that has resulted in all available land being used for crop production throughout the year. Although the soils in the catchment were predominantly clay (>65% clay) and therefore not prone to erosion, steep slopes of up to 50% and greater, contributed to rill and interrill formation in the absence of protective surface residue cover, especially during the start of the rainy season, before canopy development, when high erosive storms are common (Omwega, 1989; Mati, 2000).

Forestland around Mt. Kenya has a USLE-calculated *C*-factor of 0.007, providing nearly complete canopy and surface cover for erosion protection (Mati, 2000). USLE *C*-factors for cropland in the same area, which is similar to the Kianjuki catchment, ranged between 0.20 and 0.49, depending on growth stage and intercropping management. In Machakos, Kenya, about 75 km southeast of Nairobi, the USLE-calculated *C*-factor for corn is 0.24 (Onstad et al., 1984). The RUSLE-calculated *C*-factors for the current study fall within the range of values found for other parts of Kenya.

3.5. Support practice *P*-factor

An overall *P*-factor was computed as a product of the *P*-factors for individual support practices that were used alone or in combination to reduce erosion. The lower the *P*-factor value, the better the practice is for controlling soil erosion. The only consistent support practice observed in all profiles of the catchment was terracing. Nearly 85% of coffee grown in the catchment was grown on terraces that were 5–10 m in length. Such terraces were calculated as having a *P*-factor value between 0.5 and 0.7, depending on their grade and location within the slope profile (Table 5). Beans, bananas, and corn were not planted in contours resulting in a *P*-factor of 1.0 for contouring, and therefore, the overall support practice *P*-factor was equal to the terracing *P*-factor for each slope profile.

3.6. Average annual soil loss from the Kianjuki Catchment

Rainfall erosivity, soil erodibility, slope length and steepness, cover management, and support practice factors were calculated for all the segments that were within 304 m (1000 feet) from the top of the slope, forming the nine profiles (Table 5). Using Eq. (1), soil loss for each segment was calculated and average soil loss determined for varying *LS* slopes with all other factors incorporated. It was found that for segments with *LS*-factors between 0 and 10, predicted soil loss averaged 134 Mg ha^{-1} per year, while for *LS*-factors between 10 and 20, predicted soil loss increases to 420 Mg ha^{-1} per year, and for slopes with *LS*-factors between 20 and 30, predicted soil loss was high at 549 Mg ha^{-1} per year (Table 5).

These results compare well with separate actual erosion experiments on runoff plots in the same catchment (Angima et al., 2002) that showed water erosion on corn–bean 1-year rotation plots yield 223 Mg ha^{-1}

Table 5
Factors used to predict soil loss from water erosion with RUSLE for the Kianjuki catchment in central Kenya

Profile	Segment	R[a]	K[b]	LS	C	P	A[c]
1	1	8527	0.016	5.1	0.38	0.47	124
	2	8527	0.016	4.6	0.25	0.60	94
	3	8527	0.016	1.0	0.34	0.64	30
2	1	8527	0.016	5.3	0.35	0.47	119
	2	8527	0.016	10.6	0.35	0.60	304
3	1	8527	0.016	2.0	0.29	1.00	79
	2	8527	0.016	5.9	0.14	1.00	113
	3	8527	0.016	12.4	0.36	0.61	373
	4	8527	0.016	20.1	0.36	0.51	503
	5	8527	0.016	23.1	0.14	1.00	441
4	1	8527	0.016	2.7	0.34	1.00	125
	2	8527	0.016	7.1	0.39	0.59	223
	3	8527	0.016	14.0	0.34	0.54	351
	4	8527	0.016	18.4	0.37	0.51	474
	5	8527	0.016	29.4	0.29	0.50	582
5	1	8527	0.016	2.2	0.37	0.48	53
	2	8527	0.016	7.5	0.39	0.77	307
	3	8527	0.016	19.2	0.36	0.52	490
6	1	8527	0.016	1.4	0.34	0.48	31
	2	8527	0.016	6.0	0.32	0.96	251
	3	8527	0.016	26.3	0.35	0.53	666
7	1	8527	0.016	6.8	0.30	0.47	131
	2	8527	0.016	18.9	0.36	0.59	548
	3	8527	0.016	7.9	0.22	1.00	237
8	1	8527	0.016	9.4	0.30	0.47	181
	2	8527	0.016	19.7	0.36	0.56	542
	3	8527	0.016	11.7	0.36	0.50	287
9	1	8527	0.016	6.0	0.36	0.47	139
	2	8527	0.016	2.0	0.33	0.58	52

[a] MJ mm $ha^{-1} h^{-1}$ per year.
[b] Mg h $MJ^{-1} mm^{-1}$.
[c] Mg ha^{-1} per year.

per year of soil loss when there are no soil conservation practices in use on slopes with *LS*-factors of 8–12. The acceptable tolerable loss for renewable soil resources with this catchment area has been estimated as 2.2–4.5 Mg ha^{-1} per year for the top 0–20 cm of the soil, and 4.5–10 Mg ha^{-1} per year for the 25–50 cm layer (McCormack and Young, 1981). Using this value for soil formation means that catchment soil losses occur at a rate greater than soil formation, therefore highlighting the need for implementing conservation practices as part of future agricultural support.

An earlier study in Kenya by Mati (2000), using the old USLE, calculated rates of only 9–40 Mg ha^{-1} per year for the upper Ewaso Ngiro basin on the northern side of Mt. Kenya. However, that study area was used primarily by pasturalists, resulting in greater ground cover. In addition, that study area is on the leeward side of Mt. Kenya where there was much less rainfall, while the current study was on the windward side that was exposed to more and greater intensity rains.

The subdivision of the catchment to segments with specific *LS*-factors allows for the identification of point-specific interventions to reduce soil loss. While the *K*- and *LS*-factors may be changed gradually with time by adding organic matter and development of terraces respectively, the *C*- and *P*-factors can quickly be altered each season by farmers through contour planting and residue management to reduce the *P*- and *C*-factors, respectively. Given the limitation in farm sizes, the removal of plant residues for fodder and other uses, and less space for vegetative barriers, other support practices such as contour planting, strip cropping, and use of furrows on all slopes to reduce runoff should be used. Such practices in association with the use of terraces will decrease the overall support practice *P*-factor to below 0.2, thus lowering the predicted erosion rates to within the estimated *T*-value for the area to initiate a sustainable farming system. This can be accomplished through joint efforts by the research and the extension services by teaching and educating farmers on soil conservation methods that are appropriate for the locality and that will help them attain sustainable farming for future generations.

Calculation of the impact of water erosion on the productivity and economic viability of the current farming systems is extremely difficult because of poor empirical data. According to the only estimate available in Kenya, using USLE technology (Pagiola, 2000), terracing can be profitable under a wide range of conditions from the standpoint of estimating changes in crop productivity. Off-site impacts such as sedimentation of reservoirs and lakes were not included in the study. Benefits to the small land holder came only in the long term, with estimates showing that implementing terraces would take up to 48 years to be repaid with profit increases. In the Machakos district, which is semi-arid, the immediate cost for terracing one hectare was 3423 ksh, plus 470 ksh for maintenance each year. Although profitable, this was considered toohigh an initial investment for small scale farmers unless there was a source of off-farm income.

Use of *Calliandra calothyrsus*, a leguminous fodder tree, has been identified as a potential species that could be grown on-farm, used as a barrier species in contour hedges, and substitutes for purchased dairy meal to improve the basal fodder diet of Napier grass (*Pennisetum purpureum*). The Calliandra–Napier grass hedges have been shown to be effective in developing natural terraces (Angima et al., 2000, 2002) for substantial erosion control, while providing an economic gain to the small farmer (O'Neill et al., 2001) of up to US$ 150 per dairy cow per year.

4. Conclusions

Soil erosion by water continues to be a serious global problem, especially in Africa. The primary objective of this study was to develop a database for use in predicting erosion rates in the Kianjuki catchment in central Kenya. The computer model used to calculate average annual soil loss from the catchment was the Revised Universal Soil Loss Equation (RUSLE Version 1.06). The goal was to determine the erosion hazards in this area and target locations for appropriate initiation of conservation measures.

All factors used in RUSLE were calculated for the catchment using local data gathered during the course of this study data. The rainfall erosivity *R*-factor was 8527 $\mathrm{MJ\,mm\,ha^{-1}\,h^{-1}}$ per year and the annual average soil erodibility *K*-factor was 0.016 $\mathrm{Mg\,h\,MJ^{-1}\,mm^{-1}}$. Slopes in the catchment varied between 0 and 53% with steeper slopes having overall *LS*-values of over 17. The *C*-factor values were computed using the primary cropping patterns in the catchment, including corn–bean 1-year rotation, coffee, and banana. The only support practice (*P*-factor) commonly found throughout the catchment was terracing on slopes where coffee was grown.

Based on the data, the predicted total annual soil loss varied from one overland flow segment to the next and ranged from 134 $\mathrm{Mg\,ha^{-1}}$ per year for slopes with average *LS*-factors of 0–10 to 549 $\mathrm{Mg\,ha^{-1}}$ per year for slopes with average *LS*-factors of 20–30. These rates were greater than the estimated soil loss tolerance (*T*) for the area of 2.2–10 $\mathrm{Mg\,ha^{-1}}$ per year. The RUSLE model was able to pinpoint site-specific erosion hazards associated with each overland flow segment in the catchment for different cropping patterns and management practices. This work highlights the severity of erosion in tropical highlands of east Africa. Also, RUSLE proved to be a useful tool for determining erosion hazards in the region and pinpointed areas that would benefit meaningfully from intervention strategies. From concurrent work completed in the same region, the use of Calliandra–Napier grass hedges for developing and stabilizing terraces, might provide and economically viable method for controlling erosion.

Acknowledgements

This work was supported by funds to the National Agroforestry Research Project from the International Center for Research in Agroforestry (ICRAF), the Kenya Agricultural Research Institute (KARI), and the Swedish International Development Agency (SIDA). Travel and research for Drs. Angima and Stott were supported by the Rockefeller Foundation (Grant No. RF95022 #758). The authors thank Mr. S.P. Gachanja, Center Director for the KARI Regional Research Center that hosted this project, the two farmers, Paul and Nathan, for the use of their land for the erosion plots, and Kenneth Njagi and Patrick Njagi for their technical help in the field.

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